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OPERATION OF THICK-WALLED X-RAY TUBES ON RECTIFIED POTENTIALS[1]

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ABSTRACT

It is found that thick-walled glass, deep-therapy X-ray tubes do not reach a steady state within the first few minutes of operation on some types of generator. All thin-walled tubes tried thus far quickly reach a steady operation state. Depending upon the mode of control of the generator, the X-ray emission of a thick tube may increase or decrease by 10 to 20 per cent on mechanical or valve tube rectifiers and not reach a steady state until some 10 minutes after starting. The change in X-ray emission between the second and tenth minute of operation appears to depend upon the electrical regulation of the transformer. Cooling of the tube walls with strong air blasts delays the attainment of the steady state, but does not affect the magnitude of the net change in emission. For some generators the output remains steady if the effective tube current and voltage be maintained constant. A qualitative explanation of the effect is based on the blocking action of the high negative charge on the glass walls when the tube is cold. As the tube warms up this charge is dissipated through the increased electrical conductivity of the glass. The influence of the effect upon dosage measurements is discussed. The effect is absent when the tube is operated on nearly constant potential.

CONTENTS

I. INTRODUCTION

Until recently deep-therapy X-ray tubes of the glass-bulb type have been of soda or other soft glass, with bulbs less than 1 mm in thickness. These tubes were generally satisfactory unless placed in too restricting an inclosure, such as the smaller of the conventional "tube drums."[2]

Within the last two years a tube of Pyrex glass having walls 5 to 7 mm thick has largely replaced the common glass tubes. The pyrex tubes have several obvious advantages; for example, much higher baking temperatures can be used, with consequent improved outgassing in their manufacture. Another feature of the thick wall is the smaller likelihood of its puncture. Where a strong negative charge is built up on the inner wall the potential difference between it and the anode may rise to a point where spark over occurs through air from

[1] Presented at the annual meeting of the American Röentgen Ray Society, Detroit, September, 1932.
[2] Some qualitative experiments in this laboratory (L. S. Taylor and K. L. Tucker, B. S. Jour. Research, vol. 9 (RP475), p. 333, 1932) have shown that for satisfactorily steady operation of a thin-walled tube in such a protective inclosure, there must be a minimum spacing of about 12 to 14 inches between the bulb and any grounded metal parts.

the bulb wall to the anode lead, possibly puncturing the bulb. Sometimes without actual spark over, sufficient current may pass through the bulb at some point to cause local heating of the glass, with consequent release of gas, and a lowering of the vacuum. Thick glass walls would tend to eliminate either of these effects.

Probably most important, and unfortunately not entirely advantageous from an operation standpoint, is the influence of the thick-walled bulb upon the space charge distribution within the tube. In normal operation the inner walls of an X-ray tube acquire a strong negative charge through electrons scattered from the target or lost directly from the cathode stream. This accumulated charge reduces the field intensity at the electron source and for a given applied potential must correspondingly increase it toward the anode, resulting in a "focusing effect" of the cathode beam. This also changes the operating characteristics of the tube, in that higher potentials may be required to produce a given instantaneous electron current. With thin-walled tubes an appreciable amount of local leakage from the inner to the outer surface causes a shifting field and a varying X-ray output. For steady action of the tube it is necessary that this wall charge be either largely eliminated or made very steady. Its influence is not detrimental to the use of the tube but must be taken into consideration, with tubes operated in the usual manner.

In using several thick glass tubes it was noted that while eventually their output became extremely steady, this condition was not reached until several minutes after starting. As this delay in reaching steady operation might have a serious influence upon dosage measurements it became important to investigate the cause of the lag. In this connection we were interested too in the relationship between the effective voltage applied to the tube and the X-ray output.

II. APPARATUS

We have investigated the operation of three thick-walled X-ray tubes of different manufacture and two thin-walled tubes on six different generators: a constant potential (0.2 per cent ripple per milliampere, B. S. Standard),[3] a "constant potential" (2 per cent ripple per milliampere, commercial), a cross-arm mechanical rectifier a double-disk mechanical rectifier, a half-wave valve-tube rectifier, and a full-wave valve-tube rectifier.

To eliminate uncertain variables, each generator as used was connected to the same aerial system, meters, controls, etc.; and the several tubes successively operated in the same container—a lead-covered box 4 by 4 by 7 feet. For cooling purposes the exhausts from two pressure blowers were directed at specified times on the bulb of the X-ray tube as indicated in Figure 1. To insure proper direction of these air blasts, the air was conducted in two 2½-inch rubber tubes to within about an inch of the bulb.

Fine adjustment of the generator voltage was made by means of resistance in the transformer primary circuit after the autotransformer in the same circuit had been adjusted to a 1:1 ratio—this being the most common method of control used in practice. Peak voltages were measured with a sphere gap, which naturally interrupted the operation of the set, but was found to have no influence on the continuity

[3] L. S. Taylor, B. S. Jour. Research, vol. 2 (RP56) p. 771, 1928.

of the other measurements provided the voltage was thrown on again quickly. Average and effective (r. m. s.) high-tension voltages were measured with d. c. and a. c. meters (K_2 and K_1), respectively, in series with a 150-megohm corona-shielded resistor R;[4 5] average and effective tube currents were measured with d. c. and a. c. milliammeters (M_2 and M_1) in the high-tension circuit. A Leeds & Northrup potentiometer recorder was shunted around a resistance r_3 in series with the 150-megohm resistor as shown. This, for the voltage range used, had a sensitivity of about 350 volts per division at the 150,000 volts (average) applied across the tube. Use of the recorder simplified the process

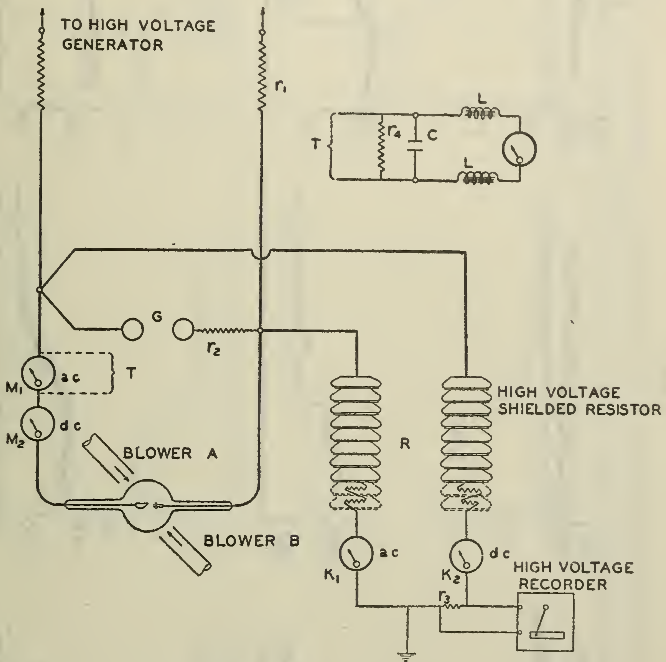

FIGURE 1.—*Schematic diagram of X-ray tube and apparatus for measuring currents and voltages*

Inset T shows filter circuit always used in conjunction with the thermomilliammeter for measuring r. m. s. tube current. A and B, blowers for cooling tube.

of making observations and also provided a very accurate record as to steadiness of the tube-operating potential.

Suitable oscillograph facilities not being readily available, voltage and current wave form changes were obtained qualitatively from other measurements with sufficient accuracy for our purposes.

The tube output was measured in terms of air ionization with a multiplate ionization chamber consisting of 11 thin aluminum plates spaced about 1 cm apart.[6] In this, one set of alternate plates was connected to a 400-volt saturation source and the other set to earth through a galvanometer, of such sensitivity that a working deflection of 40 to 50 cm was always obtainable.

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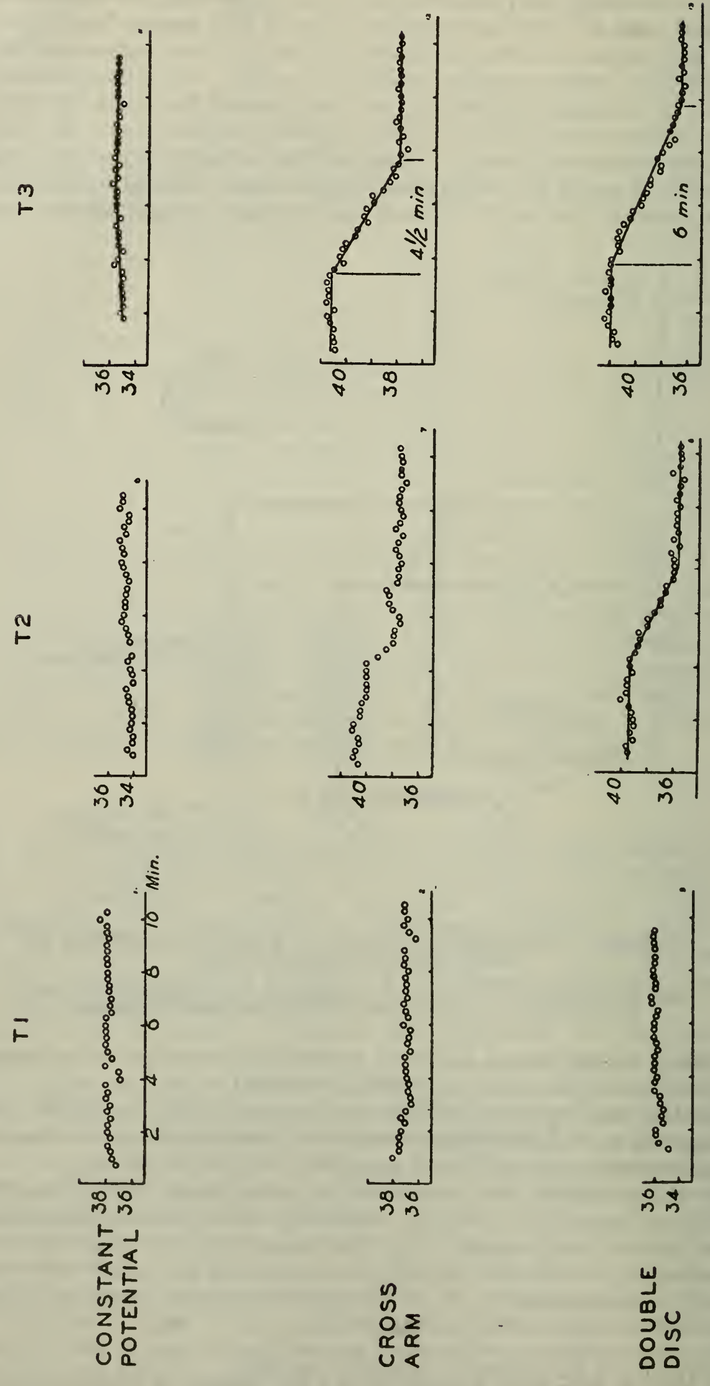
[4] L. S. Taylor, B. S. Jour. Research, vol. 5 (RP217), p. 609, 1930.
[5] L. S. Taylor, G. Singer, and C. F. Stoneburner, B. S. Jour. Research, vol. 9 (RP491), p. 561, 1932.
[6] J. L. Weatherwax "Physics of Radiology," p. 140, Paul Hoeber ,1931.


CONSTANT POTENTIAL
CROSS ARM
DOUBLE DISC
T1
T2
T3
Min.
4½ min
6 min

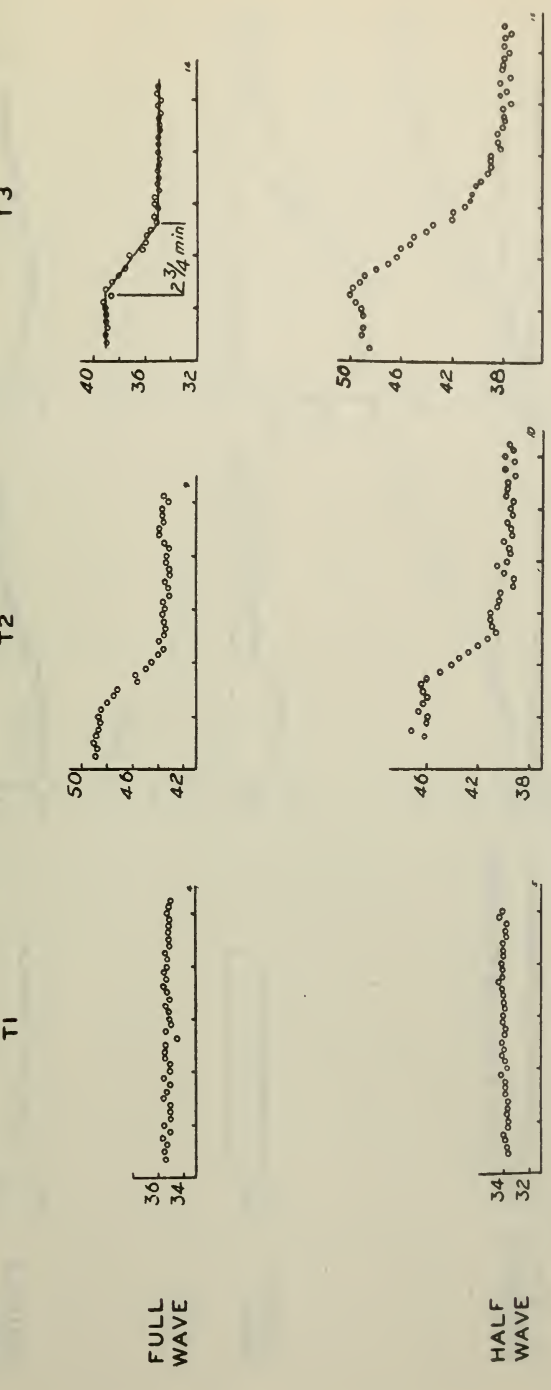
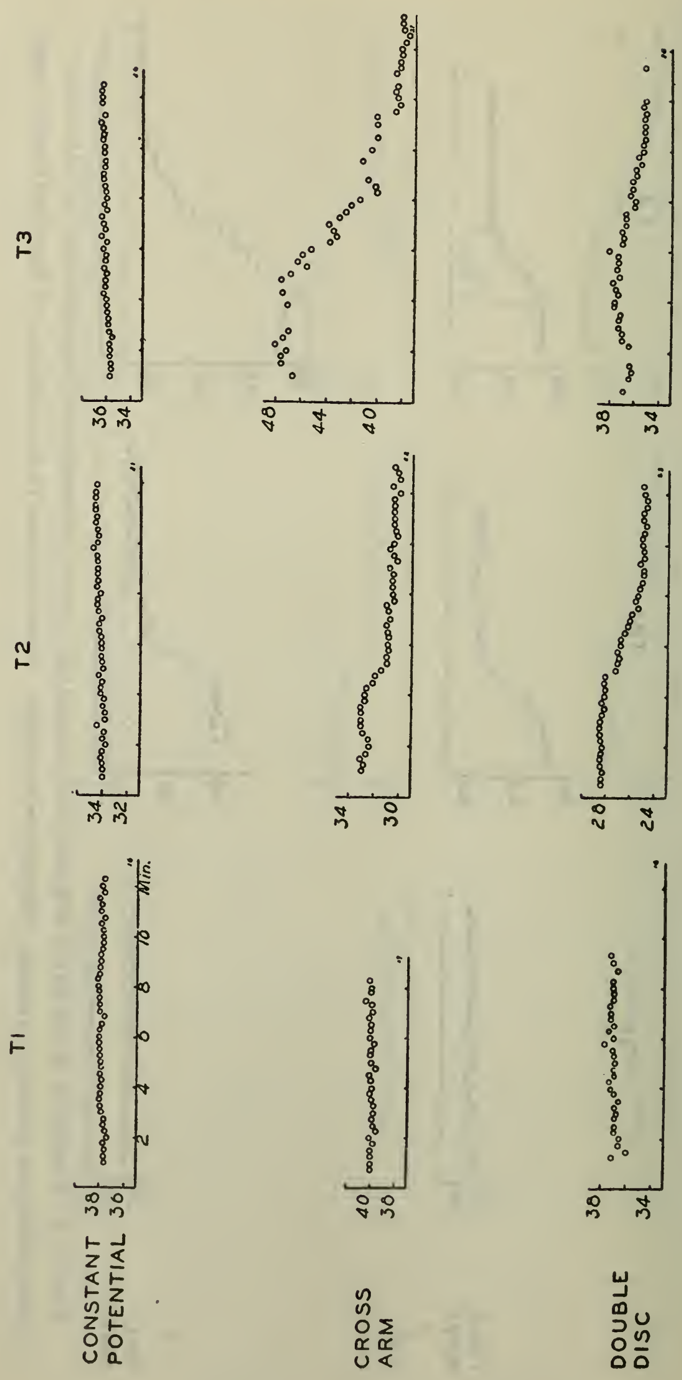


FIGURE 2.—*Changes in X-ray output with time, when average tube current and transformer primary voltage are held constant*

Abscissæ divisions show intervals of two minutes. Ordinates show X-ray output. *T1*, thin-walled tube; *T2*, thick-walled tube; *T3*, thick-walled tube (disk target).


T1
T2
T3
CONSTANT POTENTIAL
CROSS ARM
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Min.
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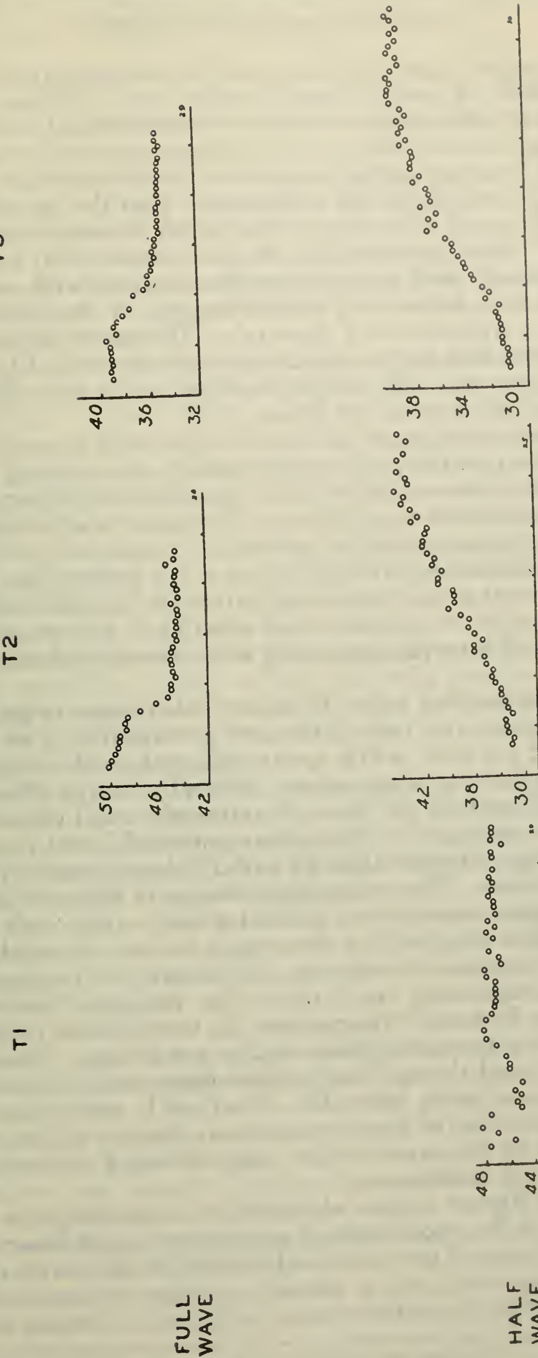

FIGURE 3.—*Changes in X-ray output with time when average tube current and average tube voltage are held constant*

Abscissæ divisions show intervals of two minutes. Ordinates show X-ray output. *T1*, thin-walled tube; *T2*, thick-walled tube; *T3*, thick-walled tube (disk target).

III. EXPERIMENTAL RESULTS

1. VARIATION OF X-RAY OUTPUT

The X-ray output was found to vary with time at a rate dependent upon the method of control, hence several such methods were employed. As seen below there was for each independent variable more than one dependent variable, so that it was not possible in any one experiment to maintain all but one of the factors constant.

It was found throughout the experiments that the two thin-walled tubes behaved exactly alike, hence the results obtained with but one, *T1*, are given. This was true also for two thick-walled tubes of the same manufacturer, so likewise the results obtained with one, *T2*, are given. These four tubes had similar targets of the massive solid tungsten type. Another thick glass tube, *T3*, was of different make, having a tungsten disk target about 6 cm in diameter and 1 mm thick. Although this tube was very similar in action to the tube *T2*, separate curves showing its behavior are given.

Figure 2 shows the changes in X-ray output with time obtained by the more common method of control, namely, by holding constant the average tube current and r. m. s. transformer primary voltage. The general procedure was as follows: Ten seconds after lighting the filament, voltage was applied to the main transformer and the autotransformer immediately cut out (set to a 1:1 ratio); the resistance was then cut out at a nearly uniform rate such that full voltage was applied to the tube 30 seconds after starting.[7] Observations were made at 15-second intervals beginning when possible 45 seconds after starting.

The curves for the thin tube, *T1*, show little change in output with duration of run, on any one of the five generators. The observed change of 1 to 2 per cent, while apparently real, is of no significance in comparison with that of the others, shown by curves *T2* and *T3*.

Tubes *T1*, *T2*, and *T3* all show an extremely small output change with time when operated on "constant potential," but on rectifiers yielding pulsating voltages tubes *T2* and *T3* show a marked decrease in output with time. The percentage change is different here from tube to tube, from generator to generator and varies with the tube current. The time required for the output to reach a steady magnitude appears to depend not only on the factors just mentioned, but also upon the transformer regulation. For example, the transition period for curves *T2* and *T3* ranges from 2¾ to 6 minutes for the three full-wave rectifiers operating under similar conditions. The greatest change in output and the one taking place most slowly occurs for the half-wave generator with tube *T3*. That such variations are not attributable to heating of the transformers, changes of line voltage, etc., was proven by the same results being obtained on starting with a cold tube and hot transformer.

The curves of Figure 3 were obtained by controlling the average voltage applied to the tube (instead of primary transformer voltage) and the tube current. These are closely similar to the curves obtained by simply holding the r. m. s. primary voltage of the transformer constant. Exception from the curves in Figure 2 is found, however,

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[7] The entire tube was at room temperature before starting. We do not recommend this fast starting of cold tubes in general practice. Those tubes used here had all been carefully tested relative to their ability to stand such treatment.

for the half-wave generator where the output increases some 25 per cent instead of decreasing by a like amount, when the transformer primary voltage is maintained constant.

2. EFFECT OF COOLING THE TUBE WALLS

In all of the observations thus far mentioned, the X-ray tube was started cold and allowed to heat up as a result of the power input of the tube without artificial cooling. If, however, with transformer primary voltage control, a strong air blast be directed on the tube bulb behind the face of the target (blower *A* in fig. 1) the output falls off very slowly with time (fig. 4, *A*) requiring some 12 minutes to reach a steady state, as compared with about 5 minutes without cooling. This may be compared with the curve for tube *T3* operating on the cross-arm rectifier.

Figure 4, *B*, shows that an air blast, such as from blower *B*, directed on the part of the tube bulb facing the target has a much more pronounced effect. In the full line curve the output falls off very slowly up to the point *a* where the blower is turned off, following which it falls off in the usual manner as compared with the normal curve. If, after a few minutes' operation without blower, this is again started, at *b* on the time curve, the output begins at once to rise toward the point *c* where turning off the blower leads in another decline. This operation was carried out in a variety of ways with always the same result. With both blowers of Figure 1 operating the output fell off only 2 or 3 per cent in 30 minutes.

It is to be concluded that so long as the X-ray tube is maintained sufficiently cool the output of the tube will remain constant with constant input, and that by cooling the hemisphere of the bulb opposite the target face the steadying effect is greater than by cooling applied behind the target.

This result suggested that by changing the power input of the tube, the bulb would be heated at a different rate and that there would be a consequent alteration in rate of change of the X-ray output. The obvious way of testing this was to change the tube current. However, because of the fact that most X-ray transformers have very poor electrical regulation, a change in tube current also changes the wave form so seriously as to mask any quantitative relation between current input at a definite potential and X-ray output. Attempts to study this change in heating on the two mechanical rectifiers were unsuccessful. Most of the runs up to this time had been made with a tube current of 5 ma, the average kilovoltage or transformer primary voltage being adjusted so as to put approximately 200 kv (peak) on the tube. If then keeping the average voltage constant the tube current be raised only 2 ma the resultant peak voltage due to distortion of the wave form reaches a dangerously high value. The same was true when regulating by transformer primary voltage. Since it is obviously impossible to control continuously the peak voltage on such a generator, other methods of control had to be sought.

Change of wave form with load was not as great in the case of the full-wave kenetron rectifier as for the mechanical rectifiers, although it was still present. The three curves in Figure 4, *C*, show the change in output with time of tube *T3*, operated on the full-wave generator, as the tube current is increased. In this the average kilovoltage was kept constant during the run. A change of current from 4 to 5 ma

changed the drop in output from 3 to 11 per cent. The corresponding final peak voltage increased from 192 to 196 kv. Changing the tube current to 6 ma, the peak voltage exceeded 200 kv so that the average voltage was dropped from 157.5 to 150 kv (average). The drop in output nevertheless increased to 18 per cent, though the lower operating voltage may have masked the true change in this case.

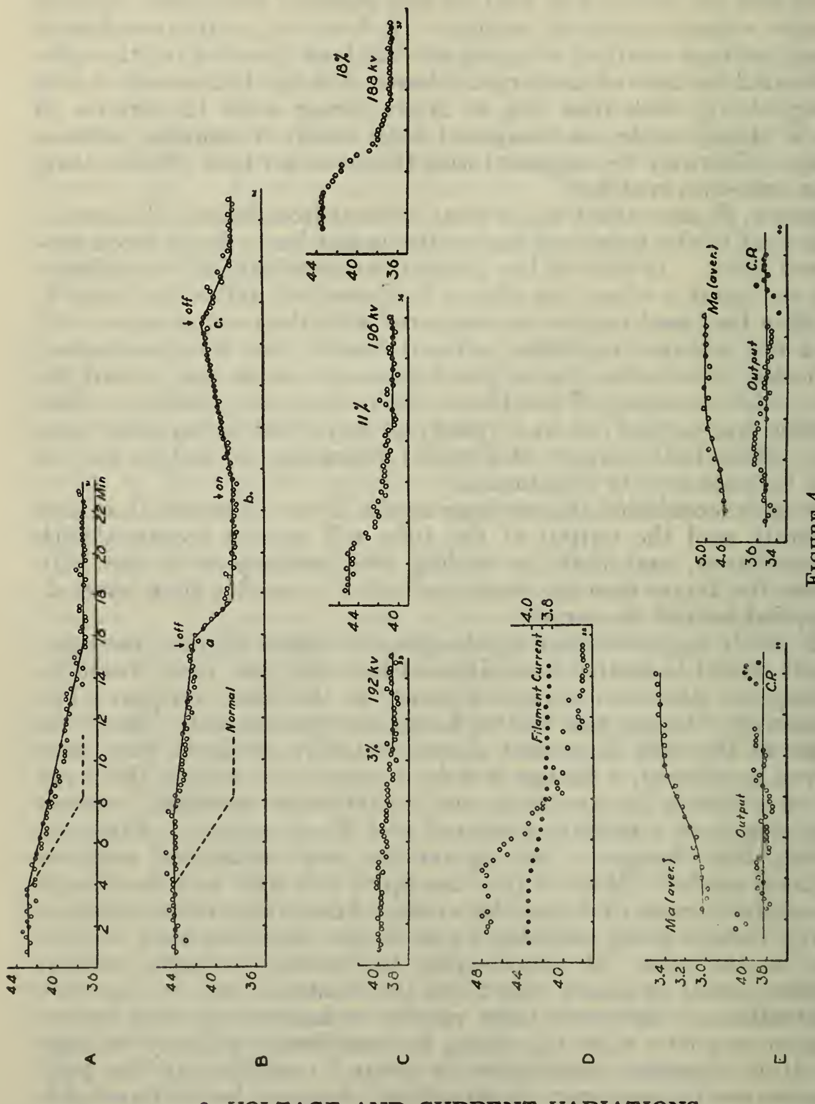

FIGURE 4

Abscissæ divisions show intervals of two minutes. Ordinates show X-ray output. Curves *A* and *B*, mechanical rectifier, average tube current and voltage held constant. Curves *C*, full-wave rectifier at 4, 5, and 6 ma (average), average voltage held constant. Curve *D*, mechanical rectifier, average tube current and voltage held constant. Curves *E*, half-wave and full-wave generators with effective tube current and voltage held constant.

3. VOLTAGE AND CURRENT VARIATIONS

Peak voltages given with the curves were in all cases measured at the end of the run, after the tube had reached its steady state. It was noted, however, that if the average tube voltage or transformer primary voltage was maintained constant through a run, the peak voltage of some generators increased from a low initial value to a

much higher final value as the tube changed in output. Figure 5 gives a group of average voltage recorder traces, from which it is found that the average voltage tended to increase along with change in tube output when the transformer primary voltage was held constant. These curves also indicate the degree of steadiness of the tube operation in these studies.

Curves *A*, Figure 6, show the variation with time of peak voltage and tube output in the case of tube *T3* on the half-wave generator operating at 84 kv (average). The output increased 17 per cent in about 10 minutes while the peak voltage increased from 133 to 173 kv, or 30 per cent. Along with this it is found that to maintain the average tube voltage constant the transformer primary voltage was increased some 12 per cent.

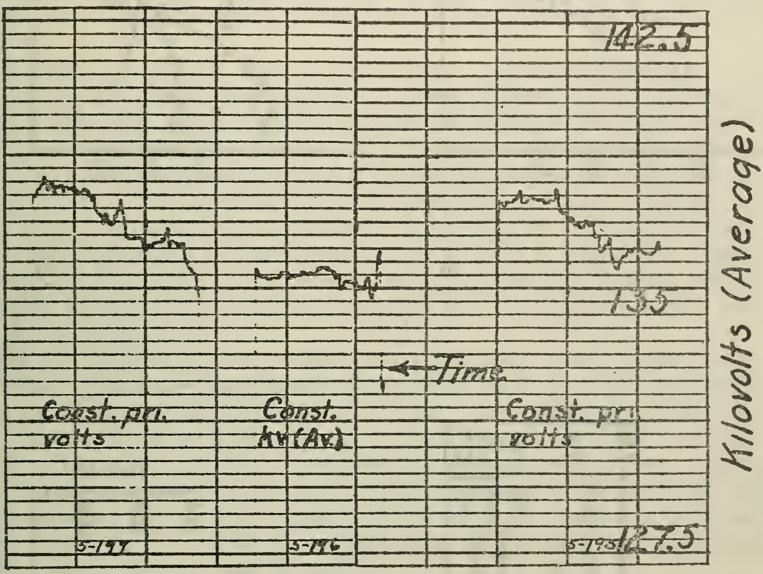

FIGURE 5.—*Traces of average tube voltage obtained with potentiometer recorder*

Time reads right to left.

On the other hand, as shown in Figure 6, *B*, if the transformer primary voltage is maintained constant, the tube output decreases about 22 per cent, the kilovoltage peak increases 26 per cent, the effective tube current decreases 28 per cent and the average kilovolts decrease 19 per cent.

In the case of the full-wave kenetron generator, Figure 6, *C*, in which the average tube current and average voltage were maintained constant, the peak voltage, effective voltage, and primary voltage also remained practically constant, while the tube output fell off with time about 11 per cent and the effective tube current also fell off about 11 per cent. In both cases above (fig. 6, *B* and *C*) the filament lighting current fell off 3 to 4 per cent.

Figure 6, *D*, shows another series of variations which are found with the double-disk mechanical rectifier. As the tube output decreases with time 22 per cent, the effective tube current decreases 22 per cent,

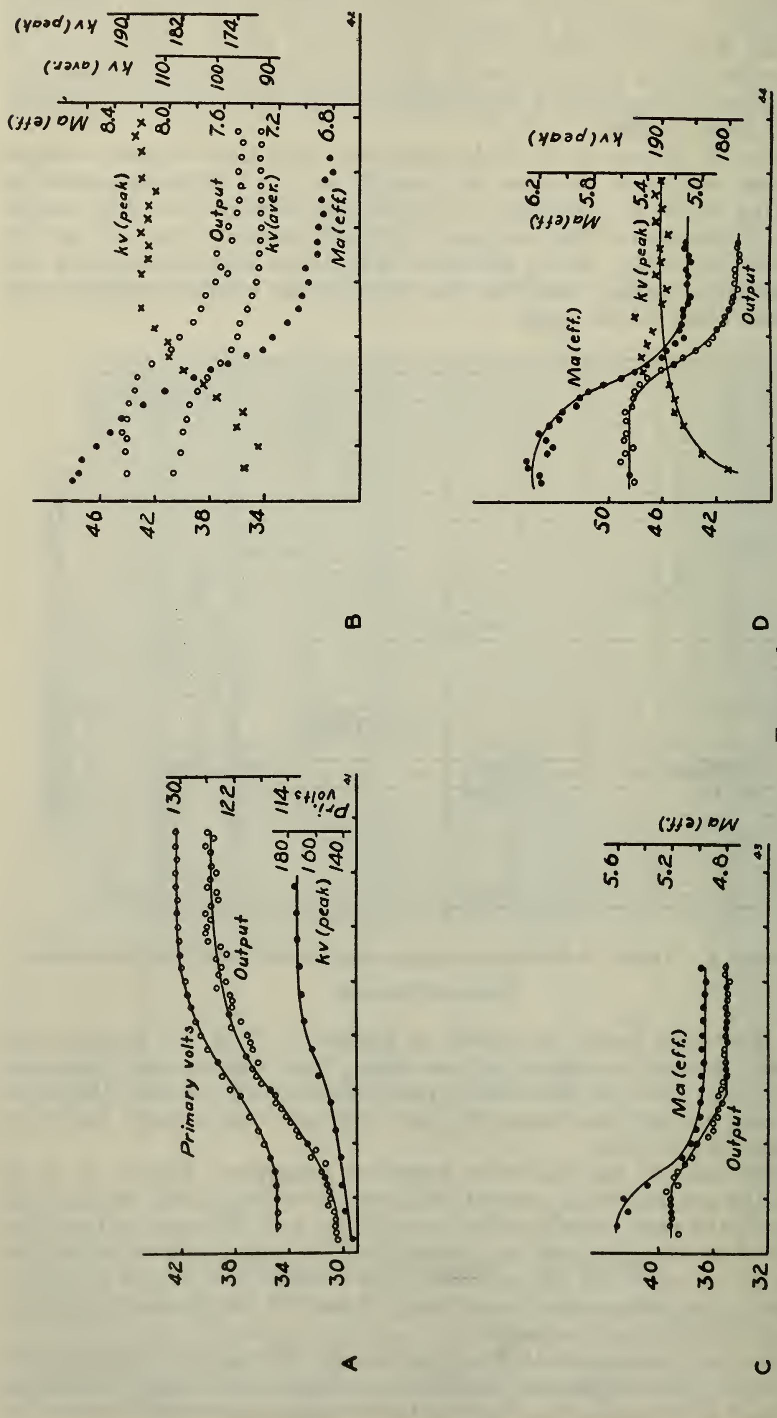

FIGURE 6

Abscissæ divisions show intervals of two minutes. Ordinates show X-ray output. Curves *A*, half wave generator with average tube current and voltage held constant. Curve *B*, half wave generator with average tube current and r. m. s. primary voltage held constant. Curve *C*, full wave generator with average tube current and voltage held constant. Curve *D*, double disk generator with average tube current and voltage held constant.

and the peak voltage increases about 6 per cent. The transformer primary voltage decreases only very slightly during this time and the kilovolts effective remain constant.

The relative variation of the several factors just shown depends largely upon the electrical regulation of the transformers and probably changes from generator to generator. In the case of a power transformer having excellent regulation the voltage variations will undoubtedly disappear.

IV. DISCUSSION

As already pointed out we were primarily interested in this variation in tube output because of its bearing on dosage measurements and also because of the possibility that means might be found for its elimination. Accordingly we will not go into a detailed discussion of the various observed effects since their full explanation becomes too involved.

Referring to Figure 4, *D*, it is found that to maintain both the average tube current and average tube voltage constant during a run, the filament lighting current must be reduced about 4 per cent, as contrasted to a negligible change when the tube is operated on constant potential. This implies that at a given instantaneous voltage near the crest the corresponding value of the tube current is higher with a cold tube with hot filament than with a hot tube with cold filament. But since the average tube current over a cycle is the same throughout the run, it follows that the current wave form for a cold tube must be relatively high and peaked as compared with a low and broad wave form for a hot tube.

Since the ordinary X-ray transformer has very poor electrical regulation, the instantaneous current drawn by the X-ray tube produces a strong reaction on the voltage wave form. Consequently, as the cold tube has a relatively high current wave for a short time, the transformer voltage is kept from reaching its normal peak value. As the tube warms up and the current wave no longer reaches such high instantaneous values, but broadens out so as to maintain the same average tube current, then the reaction on the transformer is lessened and the peak voltage rises as noted.

Figure 4, *E*, shows that the existence of a high narrow tube current wave with a cold tube is likewise borne out by the fact that when maintaining the r. m. s. tube current and r. m. s. tube voltage constant during a run, the average tube current increases continuously during the time that the tube is warming up. Similarly, Figure 6, *B*, *C*, and *D*, show that when the average tube current and voltage are maintained constant, the effective tube current decreases.

To find a cause for the change in tube current wave form we can assume that within the first half minute or less after applying voltage to the tube, the walls are charged by the scattered electrons to their maximum potential. It has been shown that if the walls of an X-ray tube be allowed to charge freely they will reach a potential very nearly that of the cathode.[8] Under such a condition the presence of this high potential sheath will exert such a strong blocking action between cathode and anode as to require much higher tube potentials to yield a given tube current. Thus in applying a pulsating voltage

[8] H. M. Terrill and C. T. Ulrey, X-ray Technology, D. Van Nostrand, 1930.

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to the tube very little tube current will pass until the voltage rises above the point where the space charge in the tube can be overcome. This action will produce a peaked current wave with the consequent effect on the voltage wave form indicated above.

As the tube warms up, the increased glass conductivity dissipates the charge on the inner walls, and the high space charge is gradually reduced to a minimum, whereupon a steady state of operation will be attained. For a given tube and generator, the temperature of the glass appears to be the chief controlling factor as suggested by the curves in Figure 4, *B*. In obtaining these curves measurements of peak voltage made simultaneously with the output measurements showed that for any given value of the output the peak voltage was the same.

When operating with a "constant potential" applied to the tube the same wall charge probably accumulates, but in that case the operating tube potential remains throughout the cycle above the point necessary to overcome the large space charge and hence supplies a constant and normal tube current. Also since the tube is operating above this point there is no change in output as the tube warms with consequent dissipation of the wall charge. Likewise since "constant potential" has little or no ripple there is no cyclic change in the reaction on the generator.

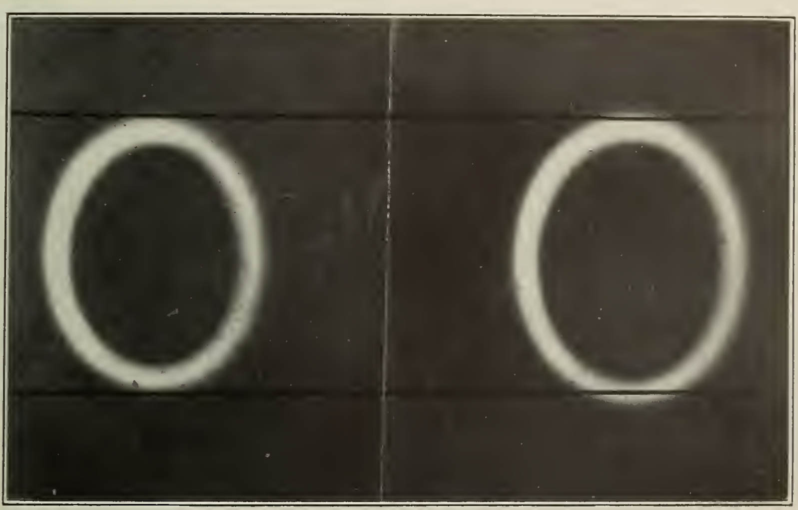
The presence of a high wall charge on a cold tube and low wall charge on a hot tube is demonstrated by the change in the size of the focal spot under these conditions. Pinhole photographs of the focal spot taken during the second two and during the last two minutes of tube operation are shown in Figure 7, *A* and *B*, respectively. It is seen that there is a definite enlargement of the focal ring when the tube is warmed. This is typical for all generators as may be expected.

In all of the output curves shown thus far the factors controlled were average tube current, average tube voltage, or r. m. s. primary voltage. As pointed out above, while these quantities were alternately maintained constant, the effective tube current and voltage and the peak voltage changed. However, as shown by Figure 4, *E*, it was found for the half and full wave kenetron generators that if the effective tube current and effective voltage were held constant that no very great change occurred in the tube output as the tube warmed. Plotted above these are curves showing the rise in average tube current occurring during the normal transition period.

In the case of one mechanical rectifier the output did not remain constant, but increased with time as contrasted with a decrease obtained by using the other methods of control.

To compare the outputs of the pulsating voltage generators with the output on constant potential, the same tube was operated on constant potential at the same effective tube current and voltage as for the half and full wave generators in Figure 4, *E*. The black dots (C. P.) represent the constant potential output under these same conditions of tube current and voltage, from which it is seen that the outputs are very nearly the same. This is in accordance with the results of an earlier investigation [9] where it was found that the outputs of all generators used in conjunction with thin walled therapy tubes were approximately alike for a given effective tube current and

[9] L. S. Taylor and K. L. Tucker, B. S. Jour. Research, vol. 9 (RP475), p. 333, 1932. L. S. Taylor, G. Singer, and C. F. Stoneburner, B. S. Jour. Research, vol. 9 (RP491), p. 561, 1932.



A, cold B, hot

FIGURE 7.—*Pinhole photographs showing variation in size of focal spot as X-ray tube warms*

voltage. This can not be generalized for all generators since, as pointed out above, similar control of the double disk rectifier did not keep a constant X-ray output.

V. EFFECT ON "DOSAGE" MEASUREMENTS

The bearing of this tube effect upon dosage measurements is fairly obvious and need not be dealt with at length.

Since the voltage is usually varying during the transition period, it is clear that the X-ray quality must also be changing. This can be remedied only by constant adjustment to keep the voltage constant. Peak voltage can not be kept constant by any simple means since the frequent operation of a sphere gap interferes with the normal operation of the equipment. However as shown by Figure 4, *E*, control of effective tube current and voltage with some generators appears to eliminate the tube effect while with others it reduces the effect somewhat.

Control of output can be effected only by means of a continuously indicating ionization chamber of some type, which, however, need not read in Röntgens. Instruments of the general type used in this paper are readily available and are in somewhat general use.

Where the X-ray output of a machine is calibrated by means of a dosage meter, measurements made during the first few minutes of tube operation may be very misleading. Depending upon the generator, these calibrations may be too high or too low, thus resulting in under or over treatment, respectively.

It should be recalled that adequate cooling [10] of the tube eliminates the change in output effect. This means that a tube having a normally falling output, if properly cooled may be operated at a higher output than otherwise possible. On the other hand, with a tube having a normally increasing output it is better to permit the tube to warm up thereby yielding a greater output at a given voltage.

In practice, the operating characteristics of the tube should be carefully determined and the "dosage" measurement procedure governed accordingly. The effect is of course absent in water cooled tubes.

This investigation has been made possible through the cordial cooperation of the American X-ray equipment manufacturers. We wish to express our indebtedness to George Singer, of this laboratory, for his assistance in carrying out many of the observations.

WASHINGTON, November 20, 1932.

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[10] The customary cooling by blowing air in one end or top of the tube container is inadequate for th elimination of this effect. The air must be applied directly to the tube walls.